SYMPOSIUM ON FUEL CELLS
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AN OUTLINE OF THE ECONOMICS OF A DOMESTIC FUEL CELL SYSTEM

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INTRODUCTION

A methane fuel cell power pack would be an attractive domestic application if the savings in fuel cost of natural gas over purchased electricity were sufficient to pay out the investment within a reasonable time or at least within the expected life of the system. Other requirements for the fuel cell system are, of course, reliability and adaptability of this type of power in the home.

This economic study is directed toward the high-temperature molten-carbonate-electrolyte type fuel cell which is under experimental investigation at the Institute of Gas Technology. This cell is capable of utilizing methane in the presence of steam at 650 to 850°C. or higher. The cell mechanism apparently involves in situ reforming of methane at the anode, followed by electrochemical oxidation of the reformate by carbonate ions. Several experimental constants relating to polarization and effective resistivity are taken from results of Shultz, et al. (2) on the molten-carbonate cell. This analysis is equally applicable to other fuel cell types for which electrode area and polarization data are available.

Because of the steep voltage-current characteristic of molten-carbonate cells, it appears unlikely that the power can be utilized under the normal variations of the domestic load without extreme voltage regulation. This would entail a substantial loss in fuel cell efficiency. Since domestic appliance load factors are usually 15 to 20%, this means the fuel cell power pack would be under low load or idling for long periods and under heavy load for short periods. The fuel cell efficiency would be further reduced by virtue of the standby heat required to maintain the operating temperature during the idling periods.

As a consequence, an electrical storage system seems to be indicated. If lead-acid storage batteries are interposed downstream of the power pack, a fairly constant voltage to load could be maintained; for periods of heavy loads several auxiliary 2-volt storage cells could be arranged to switch automatically into the circuit to maintain voltage regulation within prescribed limits. The storage system would allow reduction of the power pack capacity by a factor of 4 or 5 by virtue of nearly continuous fuel cell operation, say at a load factor of 90%, in charging the storage batteries.

The domestic system is visualized as comprising the power pack; means for recovering waste heat from the pack for water heating or other use; the storage batteries, equipped with a current limiting voltage regulator to limit the charging rate, and one or more dc inverter units to supply services requiring 60 cycle alternating current. Since inversion of dc to ac involves loss of efficiency, it would be advantageous from this standpoint to utilize dc power directly for the purely resistive loads and the ac power for resistive-inductive-capacitative loads. It is not clear, however, that the advantage of inverting only part of the load to ac would outweigh the disadvantage of needing a double wiring system.

The dc inverter might comprise: 1) motor-alternator set, 2) a multiplicity of small-capacity germanium transistorized units for individually operating radio, television, small motors and 3) preferably a several-kilowatt solid state device based on the silicon controlled rectifier (SCR). (3) With specialized frequency regulation, the SCR inverter can be sufficiently accurate to operate electric clocks. With wave form filtering, these units should be satisfactory for powering hi-fi equipment.

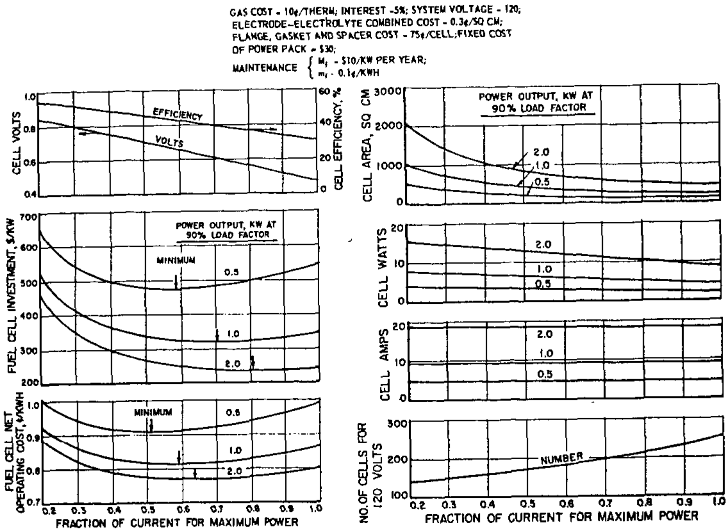

Figure 1. Effect of current density and fuel cell capacity upon cost factors and operating characteristics is demonstrated for the case where the fuel cell load factor is held at 90%, and 90% of the waste heat is credited at fuel value

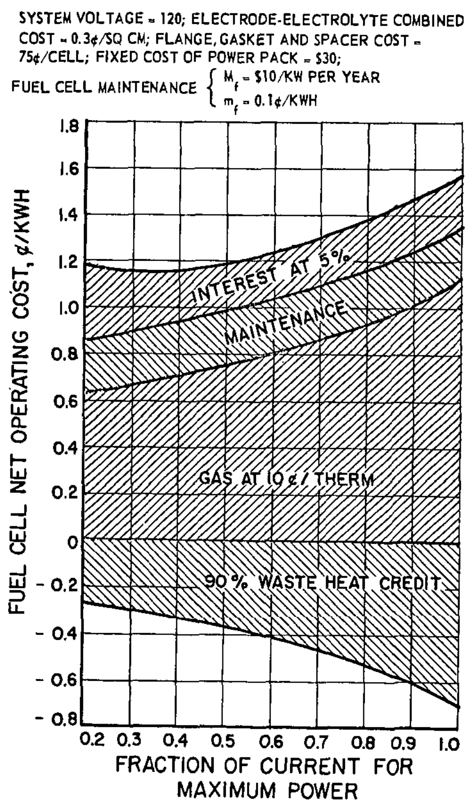

Figure 2. Fuel cell operating costs can fall within economic limits by maintaining an average load factor of 90% at 1 kw average power output

CAPITAL AND OPERATING COST RELATIONS OF POWER PACK

In this section methods of computing the estimated costs of only the fuel cell power pack are considered. This is followed in the next section by estimation of payout time of the power pack-waste heat recovery-storage battery-dc to ac inverter system. Some preliminary relations of cell performance are given here because these bear directly upon the costs.

Cell Performance

If i represents external current density, amps/sq cm; A the electrical path area per cell, sq cm; $I = iA$, the total external current, then the cell terminal voltage V is expressed by:

$$V = E^{o}_{act} - E_c - E_a - Ir_i \tag{1}$$

where E_c and E_a are the concentration polarization and activation polarization in volts, respectively, for which Austin (1) gives typical theoretical relations.

E^{o}_{act} is the actual open circuit voltage that would obtain under the concentration and temperature conditions if all polarization effects were absent. It is not necessarily equal to the experimental open circuit voltage.

r_i is the cell ohmic resistance comprising the contributions of resistivities of electrolyte, anode and cathode, and contact resistances of anode and cathode to electrolyte and to external circuitry.

For the range of current densities of interest, 10 to 40 milliamps/sq cm, the sum of the polarizations can be represented to a good approximation as a straight line: $E_c + E_a = a_p + b_p I/A$ where a_p and b_p are empirical polarization constants. If we represent $b_p/A = \beta_p r_i$ and the external load resistance $r_L = mr_i$, so that $I = V/mr_i$, then the external power, p in watts/cell, may be written:

$$p = \frac{mr_i(E^{o}_{act} - a_p)^2}{\left[(m + 1 + \beta_p)r_i\right]^2} \tag{2}$$

For fixed thicknesses of electrodes and electrolyte, r_i is inversely proportional to electrical path area A. Thus, Ar_i is practically independent of cell areas for constant temperature and constant contact resistivities. From the above definition, β_p is also a constant, and we get a direct proportion for scaling up to different cell areas:

$$(1 + \beta_p)Ar_i = \text{constant} = \left[(1 + \beta_p)Ar_i\right]_{exp} \tag{3}$$

This makes:

$$(1 + \beta_p)r_i = r_{eff}A_{exp}/A = R_{eff}/A \tag{4}$$

where r_{eff} is the experimental value of $(1 + \beta_p)r_i$, which is given by the negative slope of the linearized portion of the voltage-current density curve divided by the experimental cell area, i. e. $-\Delta V/\Delta iA_{exp}$. A particular set of data, (2) upon which part of the present study is based, for a plastic form of carbonate electrolyte between nickel and silver electrodes with 33 mole % methane-67 mole % steam at 750°C., gave $r_{eff} = 0.468$ ohms, making $R_{eff} = 10.62$ ohm-cm^2 for the reported 22.65 cm^2 cell.

In equation 2, the quantity $(E^{o}_{act} - a_p)$ represents the intercept obtained by extending to zero current density the linearized portion of the cell voltage curve. This value was 0.94 volt for the above plastic carbonate cell. Also in this equation, the external power reaches a maximum at the optimum resistance ratio $m^* = 1 + \beta_p$, for which the corresponding maximum current I^* becomes:

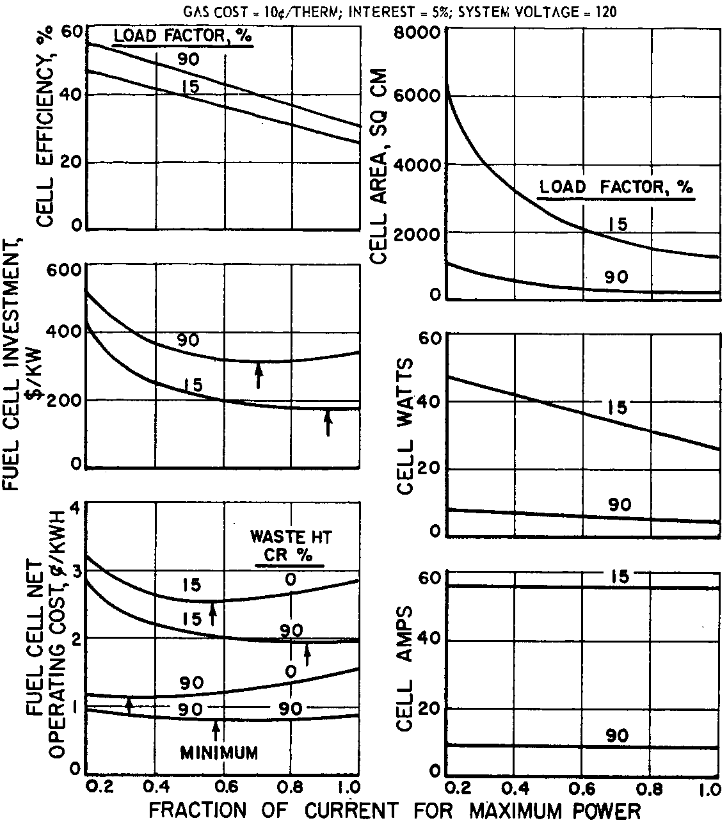

Figure 3. Load factor and waste heat credit contribute a significant effect to cost factors of a fuel cell of 1 kw average power output

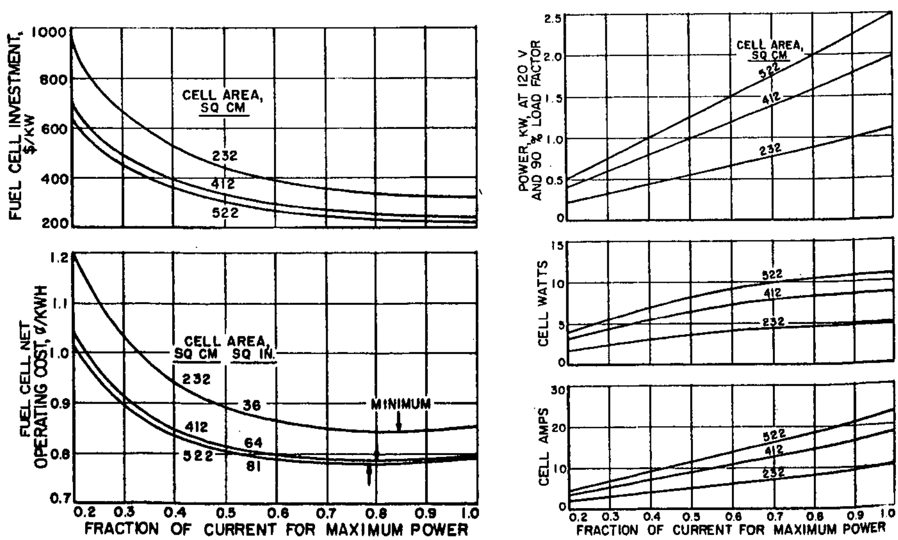

Figure 4. Effect of current density and cell area upon cost factors and operating characteristics is demonstrated for a power pack maintained at 90% load factor and credited with 90% of the waste heat

$$I^* = (E^o - a_p)A/2R_{eff} \tag{5}$$

For purposes of calculations, it is convenient to represent the actual external current I as a fraction x of the current for maximum power, $I = xI^*$. We may then write Equation 2 in the form:

$$p = (E^o_{act} - a_p)^2 (2 - x)Ax/4R_{eff} \tag{6}$$

The load resistance is expressed as:

$$r_L = mr_i = R_{eff}(2 - x)/Ax \tag{7}$$

and the cell voltage for the linearized portion of the polarization curve becomes:

$$V = (E^o_{act} - a_p)(2 - x)/2 \tag{8}$$

Costs

In setting up the fuel cell costs, we choose that the total output voltage of the power pack shall be fixed at V_t volts. Then the number of cells in series, N_C, is given by:

$$N_C = V_t/V = 2V_t/\left[(E^o_{act} - a_p)(2 - x)\right] \tag{9}$$

The capital cost of the power pack comprises a fixed cost, C_{FC}, for the casing, insulation, vent, which cost is considered independent of size over the range of capacities of interest here, plus a variable cost, C_{VP}, which is dependent upon the number and area of cells. The latter cost is split into two parts:

$$C_{VC} = N_C C_{fl} + N_C A C_{el}$$

where C_{fl} = unit combined cost in \$/cell of flanges, gaskets, piping, electrical connections, assembly

C_{el} = unit combined cost in \$/cm^2 of electrolyte and electrodes.

Thus, the principal invested in the fuel cell power pack, P_f, is as follows, based upon the above relations:

$$P_f = C_{FC} + \frac{2V_t(C_{fl} + AC_{el})}{(E^o_{act} - a_p)(2 - x)} \tag{10}$$

If g_o represents the overall fuel cell load factor, the average power output of the pack $\overline{W}$ in watts, may be stated:

$$\overline{W} = g_o p N_C = g_o(E^o_{act} - a_p)V_t Ax/2R_{eff} \tag{11}$$

The corresponding gas cost, in ¢/yr, to operate the power pack at $\overline{W}$ output is:

$$\text{Gas cost} = \frac{(3.415)(8760)(10^{-5})C_g g_o(E^o_{act} - a_p)V_t Ax}{2E_f R_{eff}} \tag{12}$$

where C_g = unit gas cost, ¢/therm

E_f = fuel cell efficiency, fractional

Perhaps 30 or 40% of the gas feed to the cells would be discharged as unreacted methane-plus-steam diluted with oxidation products of the anode reactions. The waste gas would fulfill underfiring requirements for preheating and maintaining the power pack at operating temperature. Since only a fraction of the input energy content of the gas is converted to electrical energy, ample waste heat is available which could be recovered for water heating or other use. If a fraction f_w of the waste heat is so recovered and credited at fuel value against operating costs, then the amount of credit in ¢/yr may be obtained by multiplying Equation 12 by the factor $f_w(1 - E_f)$.

An estimate of the fuel cell efficiency is required here since it bears directly upon the gas cost and waste heat credit. A relation is obtained by considering that the actual efficiency is the theoretical value diminished in proportion to the fraction of unreacted gas and in proportion to polarization and ohmic losses. We may write:

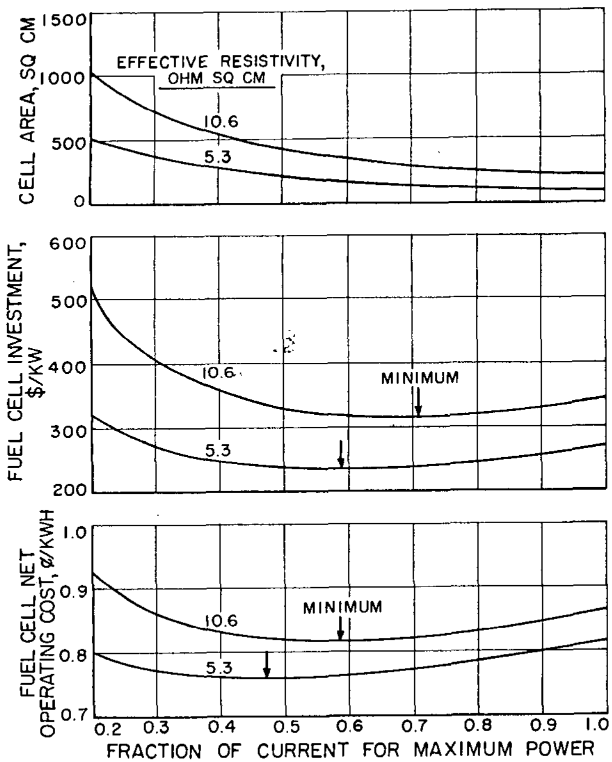

Figure 5. Costs of a methane fuel cell of 1 kw average power output at 90% load factor, with 90% waste heat credit, decrease significantly if the effective cell resistivity can be reduced by 50%

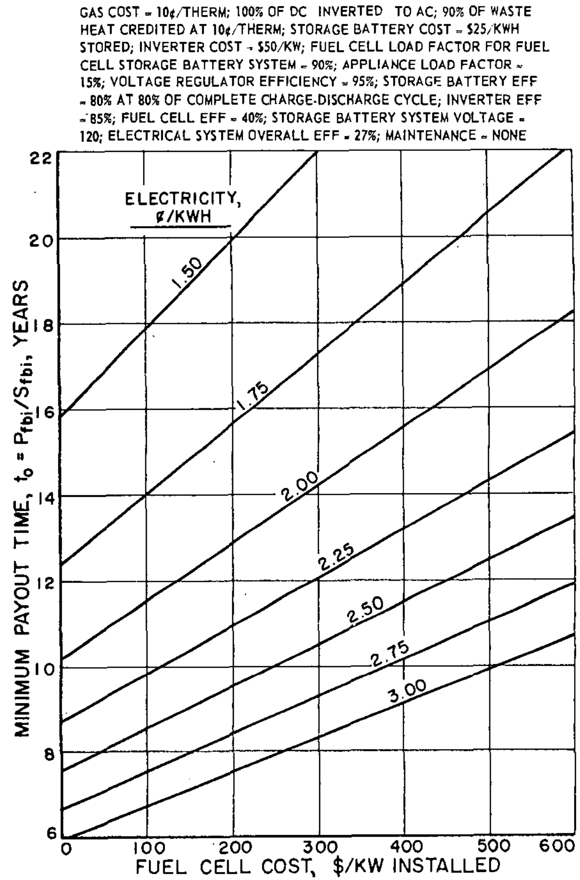

Figure 6. Effect of fuel cell cost and electric cost on payout time of fuel cell-storage battery-dc to ac converter system with 90% waste heat credit, batteries costing $25/kwh storage capacity, and inverter costing $50/kw

$$E_f = E_{theo}E'V/E^o = E_{theo}E'(E^o_{act} - a_p)(2 - x)/2E^o \qquad (13)$$

where E_{theo} = theoretical efficiency or ratio of free energy change to enthalpy change, $\Delta F/\Delta H$, at reaction temperature and concentration conditions.

E' = correction factor for unreacted fuel discharged in waste gas and for additional fuel which may be needed for underfiring.

E^o = theoretical open circuit voltage as given by the Nernst Equation, about 1 volt at 750°C. for products of methane reforming.

Fuel cell maintenance, an additional operating cost, is represented as a fixed part, M_f in \$/KW capacity per year, plus a variable portion, m_f in ¢/KWH. Since the fuel cell capacity is $\overline{W}/1000\ g_o$, and the yearly kilowatts output is 8.76 $\overline{W}$, the relationship obtains:

$$\text{Maintenance, ¢/yr} = \frac{(E^o_{act} - a_p)V_t Ax}{2R_{eff}}\left[\frac{M_f}{10} + 8.76\ g_o m_f\right] \qquad (14)$$

The total operating cost in ¢/yr of a power pack which has an arbitrary cell area A comprises the sum of interest on principal, gas cost, and maintenance less waste heat credit as given in the above relations. Dividing this sum by 8.76 $\overline{W}$ yields operating cost in ¢/KWH. Inspection of this relation shows that an optimum value of fraction of current for maximum power, x, exists such that the cost per KWH reaches a minimum.

In addition to the set of calculations which can be made for constant cell area A, it is logical also to compute on the basis of constant average power output $\overline{W}$ as parameter. To accomplish this, Equation 11 is solved for A and this result substituted into all the pertinent cost relations. In these terms, we get from Equation 10:

$$P_f = C_{FC} + \frac{2V_t C_{f1}}{(E^o_{act} - a_p)(2 - x)} + \frac{4\overline{W}R_{eff}C_{el}}{g_o(E^o_{act} - a_p)^2(2 - x)x} \qquad (15)$$

and the net operating cost, with j = interest rate, %, becomes:

$$\text{¢/KWH} = jP_f + (0.295)C_g\overline{W}\left[f_w + (1 - f_w)/E_f\right] + \overline{W}(M_f/10\ g_o + 8.76\ m_f) \qquad (16)$$

In both of these relations, the dependence on x is such that a minimum is reached. This can be computed by setting the derivatives to zero.

Calculate Results

Figs. 1 to 5 give typical indications of the manner in which molten carbonate cell performance and cost factors depend upon the operating variables for various optimistic assumptions concerning certain of the cost parameters as indicated in the captions. For all cases where the average load factor of the power pack is held at 90%, the product $E_{theo}E'$ in the fuel cell efficiency calculation is estimated at 0.65; for 15% average load factor $E_{theo}E'$ is estimated at 0.55. The unit costs C_{FC} = \$30, C_{fl} = \$0.75/cell and C_{el} = \$0.003/sq cm are considered rock bottom minima under mass production conditions.

Fig. 1 distinguishes between three average power outputs, 0.5, 1.0 and 2.0 KW at 90% load factor, indicating a rapid decrease in operating cost and investment per KW in going from 0.5 tó 1.0 KW, and a less rapid decrease in going from 1.0 to 2.0 K.W. This is a result of the fact that at a fixed current, the number of cells is fixed for 120 volt output, but the power output and electrode-electrolyte costs increase proportionately with cell area, while other fixed costs per cell have been assumed to remain the same. A power pack of 1.0 KW output at 90% load factor would be sufficient for the average home. Under the assumptions made here, the investment for this size unit reaches a minimum of \$355/KW, and fuel cell net operating cost a minimum of 0.82¢/KWH, but the minima do not occur at the same value of the operating current.

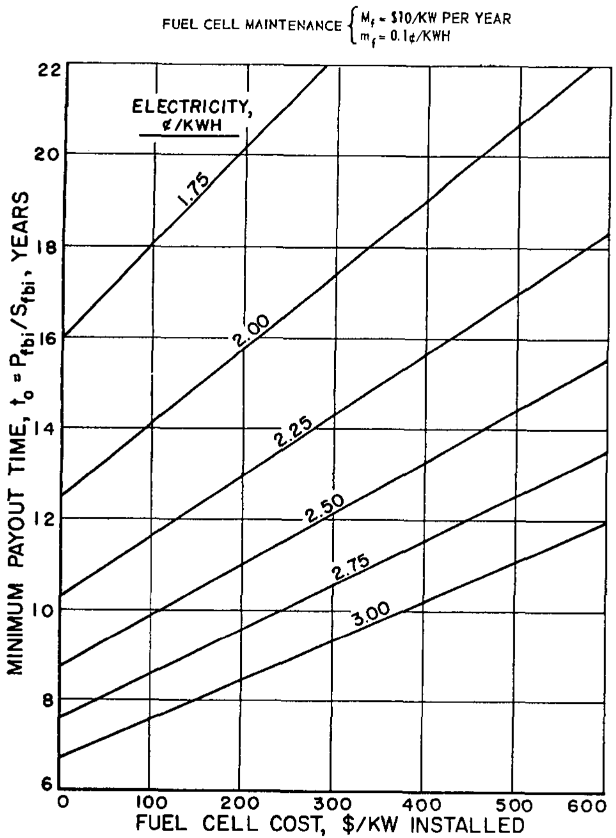

Figure 7. Effect of fuel cell cost, electric cost, and assumed fuel cell maintenance on payout time of fuel cell-storage battery-dc to ac inverter system with 90% waste heat credit, batteries costing \$25/kwh storage capacity, and inverter costing \$50/kw

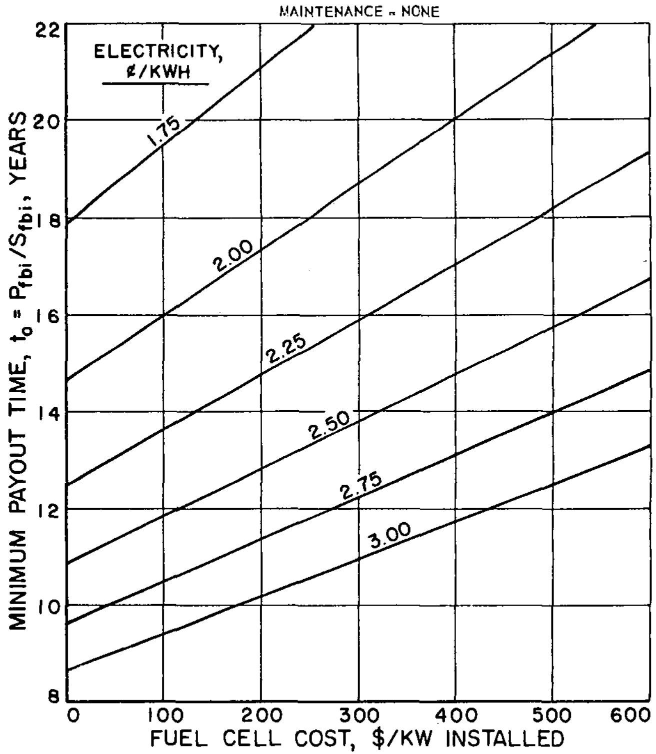

Figure 8. Effect of fuel cell cost and electric cost on payout time of fuel cell-storage battery-dc to ac inverter system with 90% waste heat credit, batteries costing \$40/kwh storage capacity, and inverter costing \$50/kw

The position of the minima shifts to the right with increasing capacity. Under present technology, cell areas are limited to a maximum of about 100 sq in or slightly over 600 sq cm. Fig. 2 gives a cumulative breakdown of operating costs for the 1 KW case of Fig. 1. The importance of the waste heat credit is stressed here because this can bring operating costs below 1¢/KWH.

The effects of varying the load factor between 15 and 90% and waste heat credit between 0 and 90% for the 1 KW case are explored in Fig. 3. The operating costs at 15% load factor approach or exceed the cost of purchased electricity, 2 to 3¢/KWH.

Since a particular f 1 cell design would have a fixed cell area, a more realistic comparison is given in Figure 4, based on constant cell areas. All the assumptions listed in caption of Fig. 1 apply here. For a fixed cell area, the power pack investment per KW is a minimum at the current corresponding to maximum power, while the operating cost approaches a minimum at a current between 75 and 85% of maximum power for the three areas shown. The number of cells, cell voltage and estimated fuel cell efficiency are the same as in Fig. 1. The power output at 120 volts increases linearly with the current, of course. For the 232 sq cm case, the average power output at 90% load factor is 0.93 KW at x = 0.84, the point of minimum operating cost. If points of constant power output are marked on the cost curves of Fig. 4, the envelope of these points defines the curves of Fig. 1. An area of significant improvement lies in reducing the effective cell resistivity. If a 50% reduction can be achieved, the investment cost may be lowered by as much as 25% and operating costs by 5 to 10%, as shown in Figure 5.

FUEL CELL SYSTEM PAYOUT TIME

Considering the potential savings in operating costs over purchased electric power, the minimum payout time, t_o in years, that the fuel cell-storage battery-dc inverter system can have is given by the general relation:

$$t_o = P_{fbi}/S_{fbi} \tag{17}$$

$$= \frac{\left[I_f + 24 I_b g_2/DV_b\right]\left[1 + f_i(1 - E_i)/E_i\right] + E_r\left[g_1 + g_2E_b\right]f_iI_i/g_i}{B\left[\frac{C_e - C_e'}{f} + C_e' + \frac{C_g\left[(1 - E_f)f_w - 1\right]}{29.33\ E_o} - m_f - (1-g')m_b\right] - \frac{24 g_2 M_b}{V_b} - M_f}$$

where $B = 87.6\ E_r(g_1 + g_2E_b)$

P_{fbi} = total principal invested in fuel cell-storage battery-dc inverter system

S_{fbi} = annual saving in operating cost of fuel cell system over purchased power

I_f = fuel cell investment cost, \$/KW installed capacity

I_b = storage battery investment cost, \$/kiloamp-hr capacity at a particular voltage

I_i = dc inverter investment cost, \$/KW installed capacity
g_1 = $g'g''$
g_2 = $g_o - g'g''$
g' = applicance load factory, fractional
g'' = fuel cell load factor during period of storage battery discharge. Here $g'' \cong 1.0$.
g_o = overall fuel cell load factor when combined battery storage, fractional
g_i = dc inverter load factor, here equal to appliance load factor.
E_r = voltage regulator efficiency, fractional.
E_b = storage battery electrical efficiency, fractional.
E_f = fuel cell thermal efficiency, fractional.
E_i = dc inverter electrical efficiency, fractional.

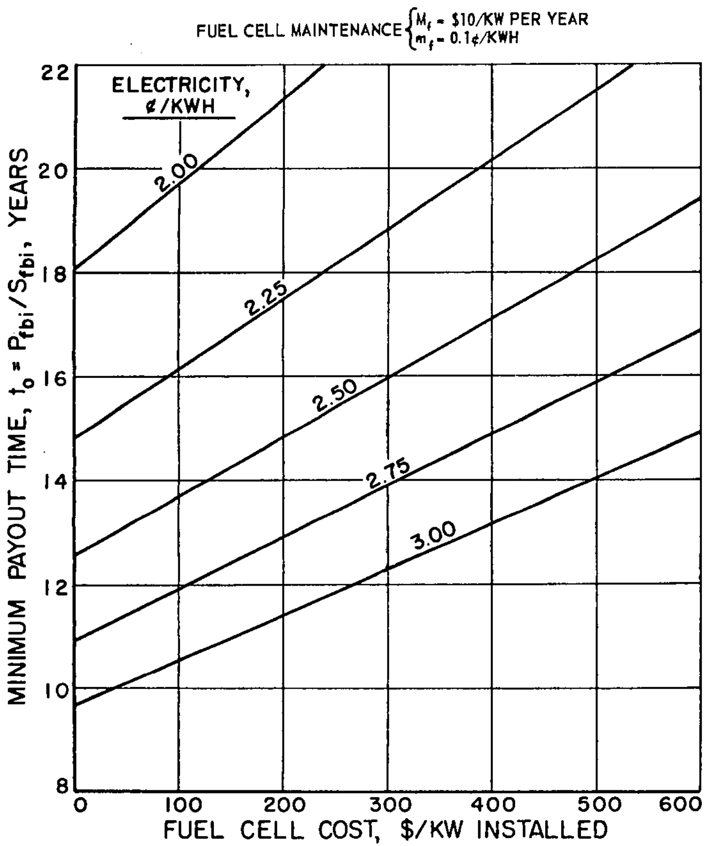

Figure 9. Effect of fuel cell cost, electric cost and assumed fuel cell maintenance on payout time of fuel cell-storage battery-dc to ac inverter system with 90% waste heat credit, batteries costing $40/kwh storage capacity, and inverter costing $50/kw

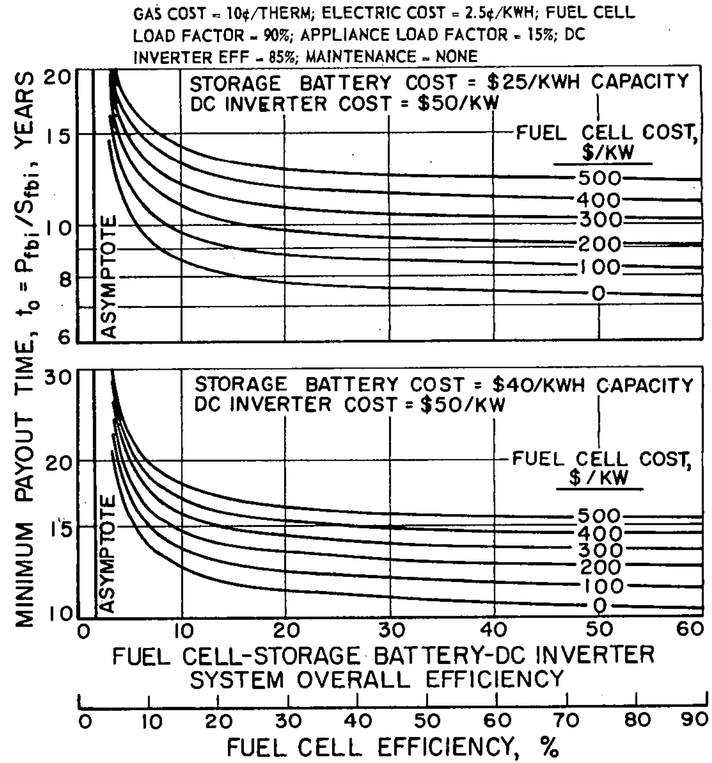

Figure 10. Effect of fuel cell system overall efficiency and fuel cell cost on payout time for fixed gas, electric, storage battery and dc inverter unit costs and with 90% waste heat credit

$E_o = E_r E_f \left[g' + (1 - g')E_b\right]\left[1 - f_i(1 - E_i)\right] =$ overall thermal efficiency of fuel cell system.

C_e = unit cost of purchased electricity prior to fuel cell installation, ¢/KWH.

C_e' = unit cost of portion of electric energy not supplied by the fuel cell, ¢/KWH.

C_g = gas cost, ¢/therm

f = fraction of total yearly electric load supplied by fuel cell.

f_w = fraction of fuel cell waste heat which is utilized in other appliances and credited to fuel cell at fuel value.

f_i = fraction of dc power inverted to ac.

D = fraction discharge of storage batteries; i.e., 1.0 = full discharge during cycle.

V_b = storage battery voltage.

m_f = variable maintenance cost of fuel cell, ¢/KWH output.

M_f = fixed maintenance cost of fuel cell, \$/year per KW installed capacity.

m_b = variable maintenance cost of storage battery, ¢/KWH delivered through battery.

M_b = fixed maintenance cost of storage battery, ¢/year per kiloamp-hr installed capacity.

24 = factor which arises because a 24-hr discharge-charge cycle of the storage batteries is assumed.

The payout time in the above relation is the minimum time because interest on the invested capital is not included. If intereat at j% is considered, the corrected payout time, t, increases in accordance with the following expression based on differential compounding:

$$t = -\left[\frac{100}{j}\right] \ln\,(1.0 - jt_o/100) \tag{18}$$

Equation 17 contains about all of the tangible parameters that can be written into the fuel cell system. This relationship is quite flexible since it permits calculation of any combination such as fuel cell with inverter alone without waste heat recovery or fuel cell-storage battery without inverter by assigning zero values to the appropriate parameters.

In deriving Equation 17, certain intermediate results are of interest. The ratio of total investment of the fuel cell-storage battery system P_{fb} to total investment of the fuel cell alone P_f is given by:

$$\frac{P_{fb}}{P_f} = \left[\frac{g'}{g_1 + g_2 E_b}\right]\left[1 + \frac{24 g_2 I_b}{DV_b I_f}\right] \tag{19}$$

In most cases at low applicance load factors and fuel cell investments of \$300/KW or higher, this ratio is less than unity, depending, of course, upon the other parameters. The total principal invested in the fuel cell-storage battery-dc inverter system may be written in the form:

$$P_{fbi} = C_f I_f + C_b I_b + C_i I_i \tag{20}$$

where C_f, C_i = capacity of fuel cell power pack and inverter, respectively, KW

C_b = capacity of storage batteries, kiloamp-hr at system voltage

If L denotes the yearly electric load, KWH, then in terms of parameters already defined:

$$C_f = \frac{Lf\left[1 + f_i(1 - E_i)/E_i\right]}{8760\ E_r(g_1 + g_2 E_b)} \tag{21}$$

$$C_b = \frac{Lf\left[1 + f_i(1 - E_i)/E_i\right]}{365DV_bE_r(E_b + g_1/g_2)} \quad (22)$$

$$C_i = \frac{Lf\ f_i}{8760g_i} \quad (23)$$

Without storage batteris and inverter, the fuel cell capacity increases to:

$$C_f = \frac{Lf}{8760E_rg'}$$

As an example, if L = 5000 KWH, f = 1.0, f_i = 1.0, D = 0.80, V_b = 120, E_r = 0.95, E_b = 0.80, E_i = 0.85, g' = 0.15, g_1 = 0.15, g_2 = 0.90 - 0.15 or 0.75, then C_b = 0.177 kiloamp-hr at 120 volts for a 15% applicance load factor. This is equivalent to a total electrical storage of 21 KWH. In comparison, the storage capacity of a 6 or 12-volt good grade automobile battery is about 0.75 - 0.85 KWH. This gives an indication of the bulk volume since 21 KWH is equal to about 26 automobile batteries. In this same example C_f = 0.94 KW with storage batteries or 4.0 KW without storage batteries and inverter, indicating a greater than four-fold reduction in power pack capacity by virtue of electrical storage.

Computed minimum payout times for the fuel cell-storage battery-dc inverter system are shown in Figs. 6 to 11 for various assumptions of the cost and operating parameters as indicated in the captions. Certain of these assumptions are admittedly optimistic, particularly 80% electrical efficiency of storage batteries discharged to a depth of 80% and $50/KW for dc inverters. If the battery discharge depth were limited to 60% with electrical efficiency less than 80%, the payout times would increase significantly. In general, if waste heat were not recovered, the payout times would increase by 25 to 35% over the results shown here. If a dc inverter were not used, the payout times would be reduced by 30 to 40% of the values shown.

With storage batteries at a minimum cost of $25/KWH storage capacity and no fuel cell or battery maintenance, we have a minimum payout time of 10 years if purchased power costs 2.5¢/KWH and fuel cell investment cost is $300/KW (Figure 6). This payout time increases to 12 years with the fuel cell maintenance cost assumed in Fig. 7. With higher priced storage batteries, $40/KWH, (Figs. 8 and 9) and electricity at 2.5¢/KWH, a minimum payout time of 10 years cannot be achieved no matter what the fuel cell investment cost.

Figures 10 and 11 explore the effects of overall system efficiency on the payout times for a fixed purchased power cost of 2.5¢/KWH. As is evident, the payout time decreases sharply at system overall efficiencies up to 20%. The slope of the curves becomes nearly horizontal at higher efficiencies, indicating that, with waste heat recovery, the effect of efficiency in going from a fuel cell efficiency of 30% to 60% is not of great significance, except insofar as this determines the amount of waste heat available. At fuel cell efficiencies much below 20%, the quantity of waste heat becomes excessive.

CONCLUSIONS

Relationships have been presented which enable one to judge the conditions under which fuel cells would be economically attractive in a domestic application. With certain experimentally evaluated constants, these relations were applied to the high-temperature molten carbonate cell to arrive at estimates of capital and operating costs. It appeared that these could be sufficiently low that the saving against purchased power should eventually pay out the investment. In a more general manner, the payout time was set up in relation with unit investment costs and operating parameters of fuel cell, storage batteries and inverter. With representative assumptions, a payout time of 10 years for the system is attainable only under the best conditions.

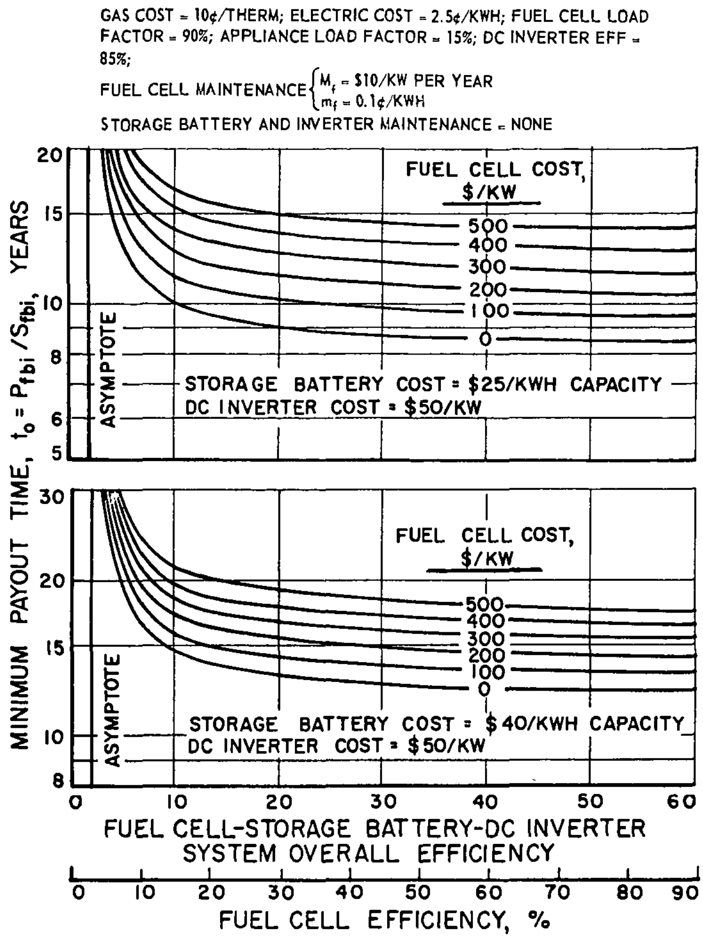

Figure 11. Effect of fuel cell system overall efficiency, fuel cell cost and assumed fuel cell maintenance, on payout time for fixed gas, electric, storage battery and dc inverter unit costs, and with 90% waste heat credit

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